

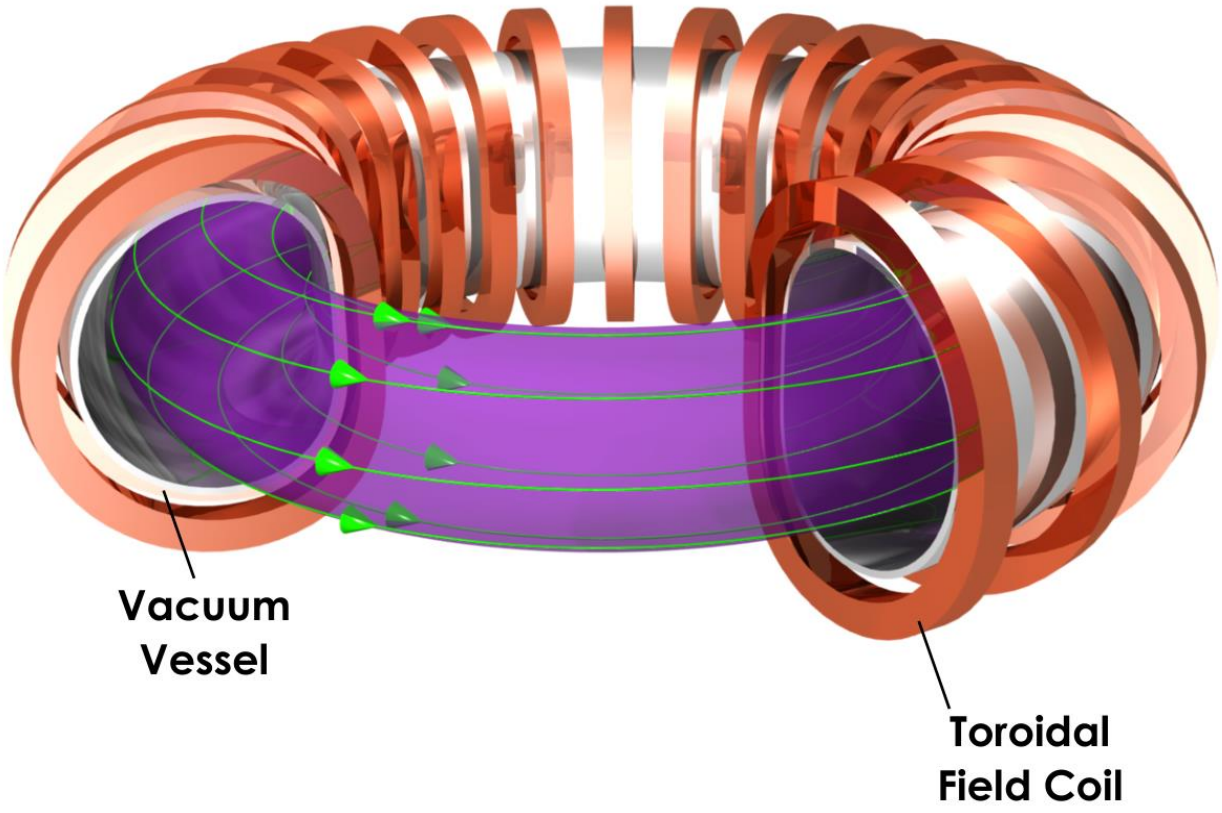
OBSTÁCULOS E SOLUÇÕES AO CONFINAMENTO MAGNÉTICO DE PLASMAS

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Disciplina: Eletrodinâmica Clássica I

Por que confinar Plasma?

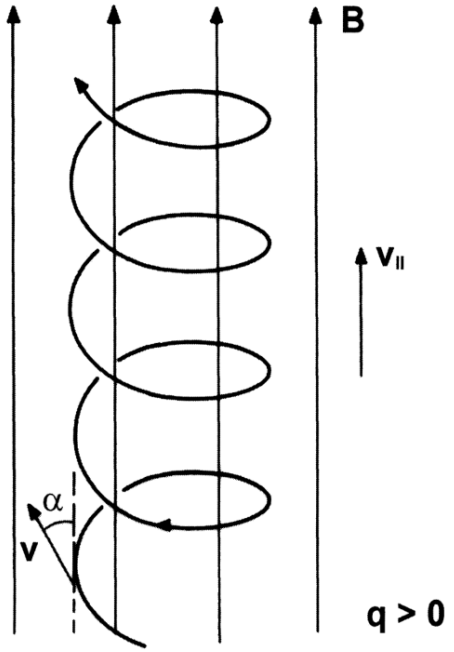
- Consumo de energia crescente
- Fusão Termonuclear Controlada



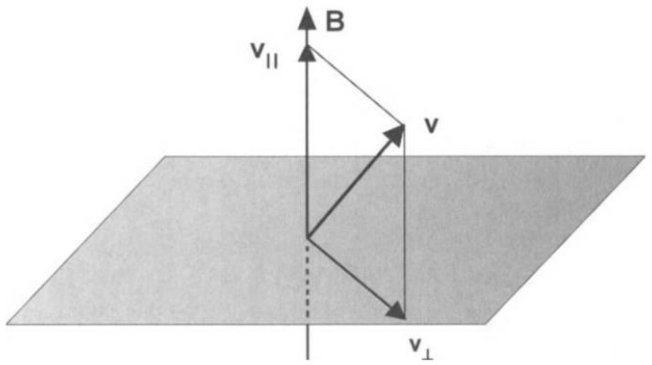
Movimento Partículas em Campos Magnetostáticos e Uniformes

$$\boldsymbol{F} = m\frac{d\boldsymbol{v}}{dt} = q(\boldsymbol{v} \times \boldsymbol{B})$$

$$\omega = \frac{|q|B}{m} \qquad r = \frac{mv_{\perp}}{|q|B}$$



Centro Guia segue as linhas de campo magnético

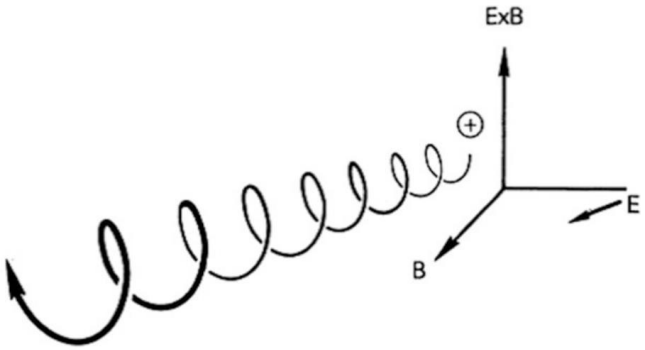


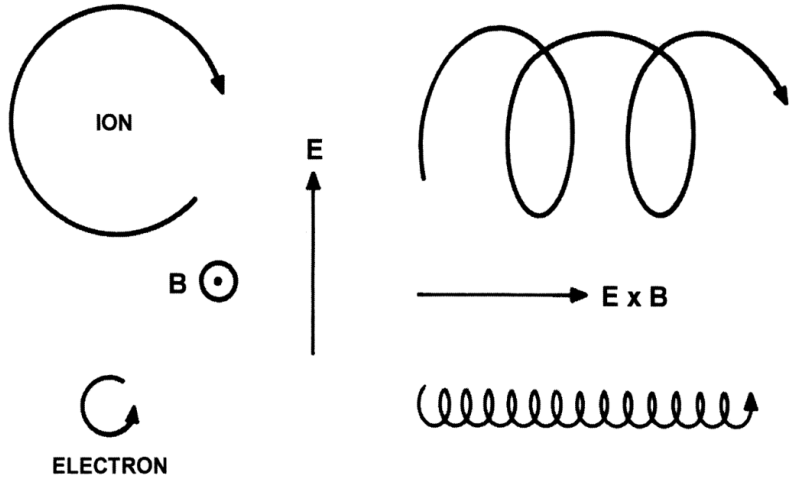
Adição de um Campo Eletrostático

A presença de campo $\boldsymbol{F}$ adiciona uma deriva do CG na direção perpendicular a $\boldsymbol{B}$ e $\boldsymbol{F}$

$$\boldsymbol{v_F} = \frac{\boldsymbol{F} \times \boldsymbol{B}}{qB^2} = \frac{\boldsymbol{E} \times \boldsymbol{B}}{B^2}$$

$$r = \frac{mv_\perp}{|q|B}$$



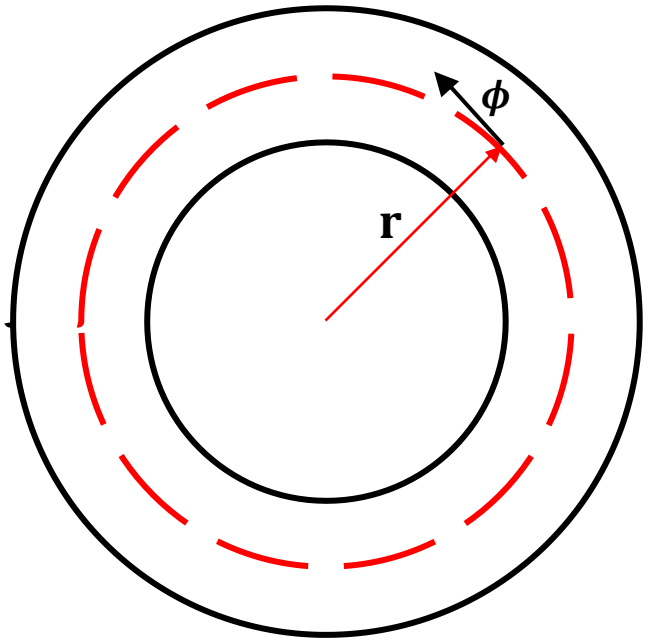


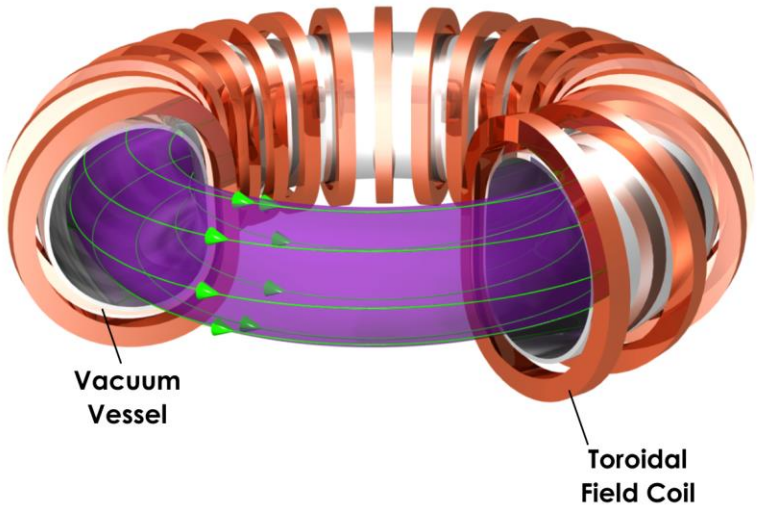
Tokamaks (60’s)

Na década de 60 os russos propuseram* este sistema toroidal.

Tudo parecia certo...mas não funcionava!

O campo magnético toroidal possui **gradientes** e **curvatura**



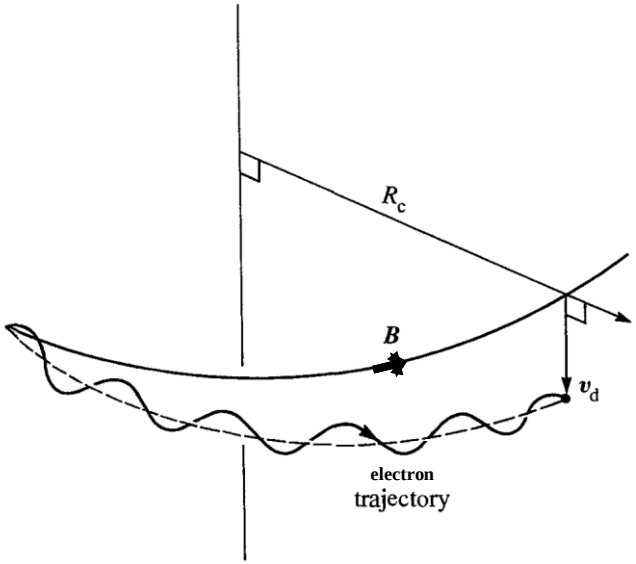


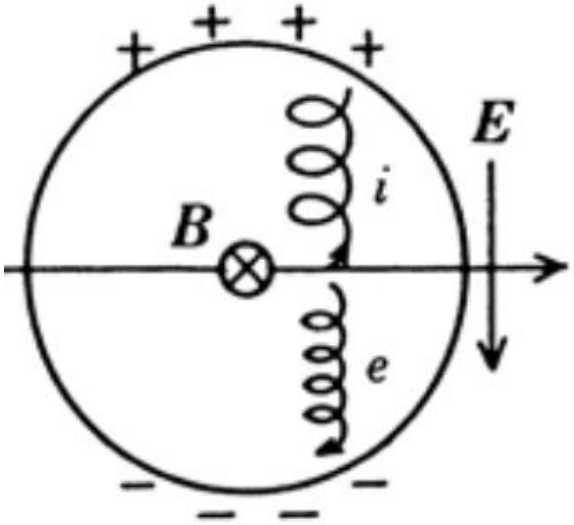
Deriva de gradiente-curvatura

$$\boldsymbol{v_F} = \frac{\boldsymbol{F} \times \boldsymbol{B}}{qB^2}$$

$$\boldsymbol{v_{GC}} = \frac{m}{qBr}\left(v_{||}^2 + \frac{v_\perp^2}{2}\right)\boldsymbol{z}$$

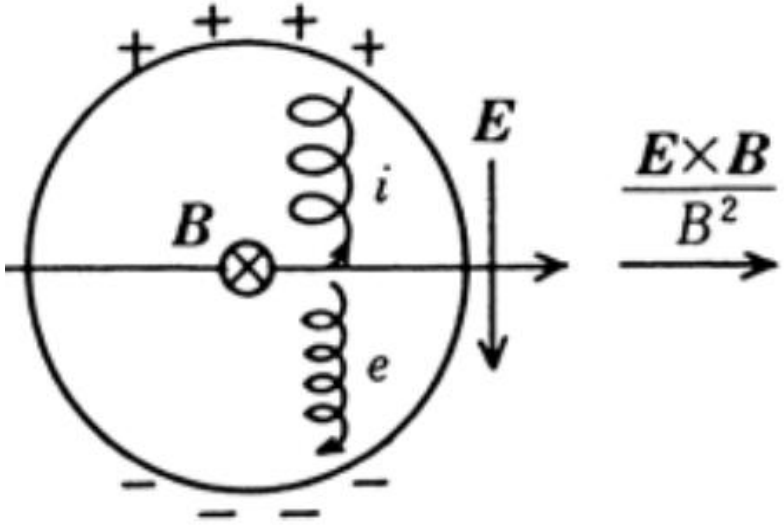
Força Centrífuga/ $\nabla \boldsymbol{B}$





Derivas em tokamaks

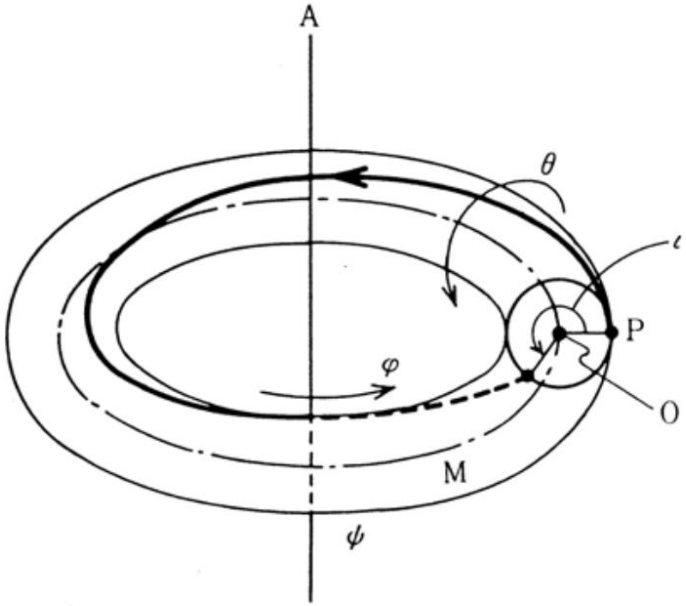
Problema: Um campo magnético puramente toroidal não é capaz de confinar um plasma

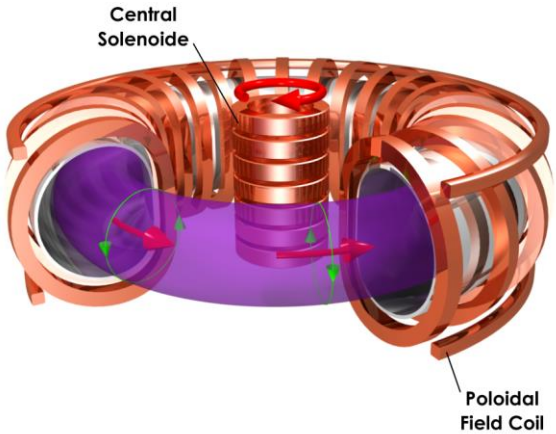


Transformada Rotacional

- "Torcer" o campo magnético
- Adição de um campo poloidal (θ)

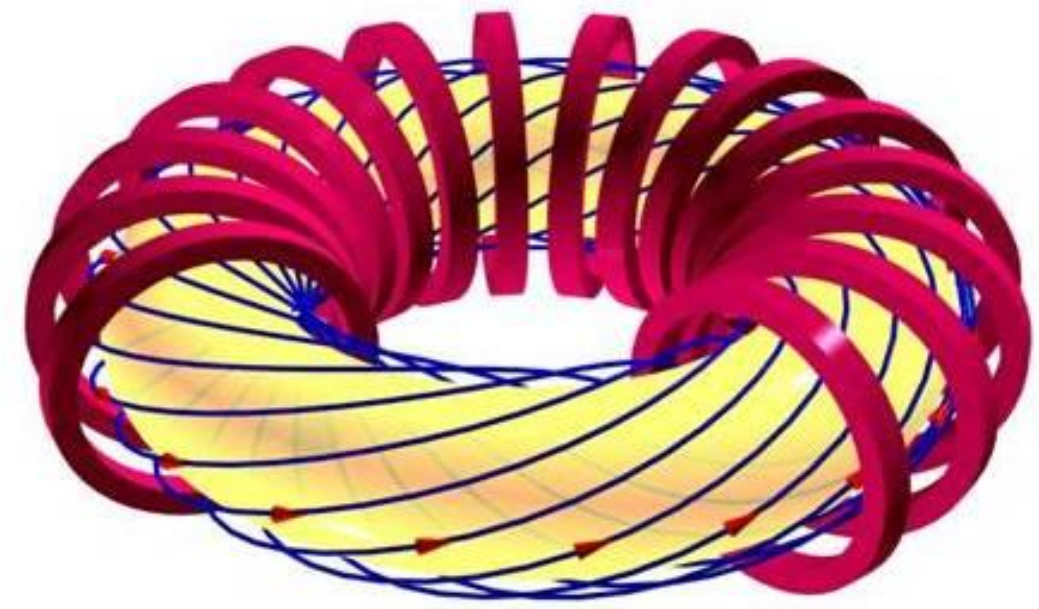
$$\frac{\Delta\phi}{\Delta\theta} = \frac{2\pi R}{r\iota} = \frac{B_\phi}{B_\theta} \quad \Rightarrow \quad \frac{\iota}{2\pi} = \frac{R}{r}\frac{B_\theta}{B_\phi}$$





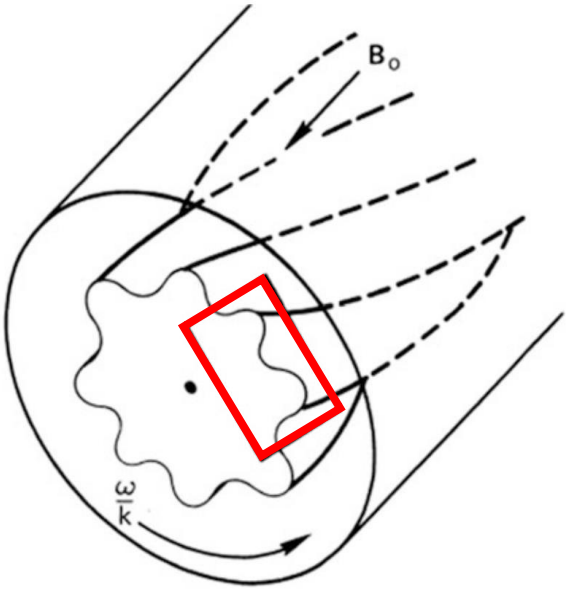
Campo de um Tokamak

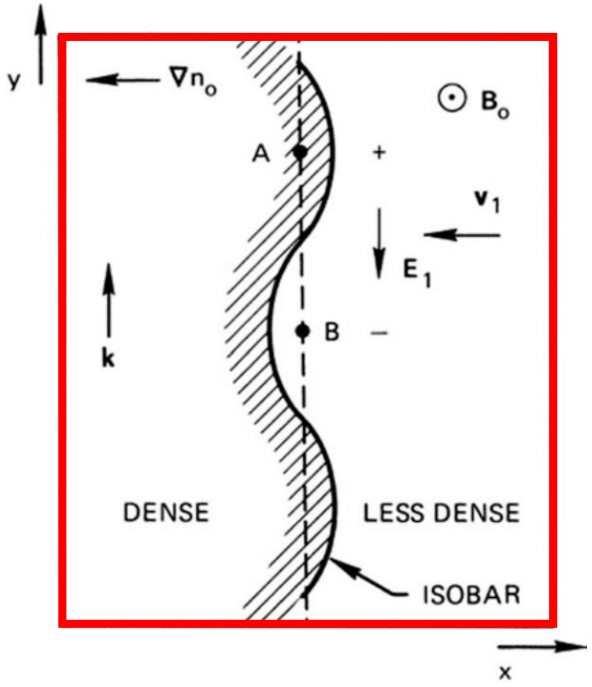
Devido a "torção" das linhas de campo, o efeito de polarização se anula



Mas nem tudo são flores

- Transporte não-difusivo (muito rápido) na borda do plasma

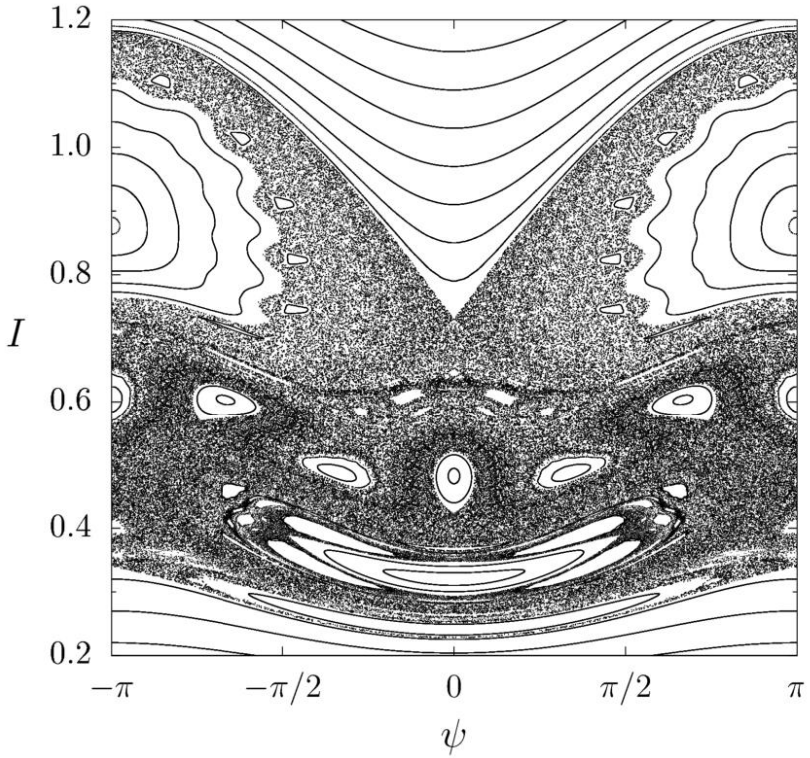




Mas nem tudo são flores

$$\frac{d\boldsymbol{r}}{dt} = v_{||}\frac{\boldsymbol{B}}{B} + \frac{\boldsymbol{E_1} \times \boldsymbol{B}}{B^2}$$

- Sistema não-integrável
- Trajetórias caóticas



Conclusões

- O comportamento do plasma é determinado pelos campos
- Um campo puramente toroidal não confina um plasma
- Necessidades de campos poloidais para impedir a polarização do plasma e o transporte de partículas
- Deriva $\boldsymbol{E} \times \boldsymbol{B}$ ainda dá dores de cabeça!

Para saber mais

- BITTENCOURT, José A. **Fundamentals of plasma physics**. Springer Science & Business Media, 2013.
- SHAFRANOV, Vitalii D. et al. On the history of the research into controlled thermonuclear fusion. **Physics-Uspekhi**, v. 44, n. 8, p. 835-843, 2001.
- **Oscilation Control Group (IFUSP)**: http://portal.if.usp.br/controle/
- Experimento de plasma remoto que evidencia o confinamento magnético: https://scied-web.pppl.gov/RGDX/#

